Strain-modulated epitaxy: A flexible approach to 3-D band structure engineering without surface patterning

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Thin compliant growth substrates have been used to reduce the strain in lattice-mismatched overlayers during epitaxial growth. This letter reports a new thin compliant substrate technology which allows these thin substrates to be *patterned* on the bottom, bonded surface. This lateral strain variation (inverted stressor) in the growing film can be combined with the additional effects of strain-dependent growth kinetics to realize the lateral control of composition and thickness without any surface topography on the substrate. Initial demonstrations of the growth of InGaAs on GaAs bottom-patterned thin substrates are presented herein. © *1996 American Institute of Physics.* [S0003-6951(96)03628-5]

During the past 30 years, band structure engineering has led to numerous photonic and electronic device innovations. One-dimensional band structure control, typically realized in the growth direction, is simply produced by heterojunction formation during epitaxial growth. Two- or three-dimensional band engineering must be produced using potential changes realized perpendicular to the growth direction, thus requiring the lateral control of material properties. Such structures can be produced either during the growth process or by processing after growth. For example, the lateral control of material properties can be achieved with the growth of heterojunctions on patterned[1] or vicinal substrates[2] to produce quantum wires. Strain has also emerged as a means of producing lateral changes in material properties. Island nucleation is favored under certain growth conditions over two-dimensional growth during the deposition of highly strained materials.[3,4] In addition, strain has been used to produce confinement through post-growth processing using *stressors*, which can be formed by patterning and etching a strained overlayer in a mismatched multilayer thin film.[5] The stressors create lateral variations in the elastic deformation which change the band structure of the material.

The production of lateral confinement potentials during epitaxy offers inherent advantages over structures formed by pre- and post-growth processing. Pre-growth patterning on the growth surface places boundaries on the control of desired properties due to facet-dependent growth kinetics. Post-growth patterning near the active region may create defects which degrade the quality of the active region where the carriers are confined, thus leading to degraded carrier properties.[6] A flexible method for creating lateral confinement without such patterning of the epilayer or substrate surface would expand the range of choices in the design of the confinement potential. Such a technique, called *strain-modulated epitaxy*, which utilizes thin, compliant substrates which are patterned on the bottom, bonded surface, is reported in this paper. The diversity of this method makes it possible to consider it for applications which include higher-order quantum confined structures and multiwavelength optoelectronic devices.

Recently, compliant substrate technology, a new approach to the growth of strained materials, has been proposed and demonstrated.[7–9] This technique functions on the principle that the strain in a lattice-mismatched overlayer can be reduced via partial accommodation of the total strain in a *compliant* substrate. In the case of lattice-mismatched growth by common epitaxial growth techniques on conventional substrates, the epitaxial layer is much thinner than the substrate, and thus virtually all the strain resides in the epitaxial layer. On the other hand, the thickness of a compliant substrate may be on the order of or less than that of the epitaxial layer.[10] In this case, the strain produced during growth will be partitioned between the substrate and the lattice-mismatched epitaxial layer according to[11]

$$\epsilon_f = \frac{h_s}{h_f + h_s}\, \epsilon_0,$$

where ϵ_f is the new strain film, ϵ_0 is the total strain of the system, h_s is the thickness of the substrate, and h_f is the thickness of the grown film. Compliant substrates can be used to extend the conventional critical thickness as a result of the substrate and the film sharing the total strain elastically. In addition, compliant substrates can be used to reduce the defect density in a mismatched overlayer, enabling the substrate to relax before the epitaxial layer.[12]

Previous demonstrations of compliant substrate technologies have included GaAs membranes[7] and silicon-on-insulator (SOI) material.[8,9] We have recently proposed and demonstrated a new type of compliant substrate technology based on bonded and etched thin film substrates.[13] Bonded thin film substrates enable the production of thin film (∼hundreds of Å), large area (∼cm^2) materials and allow processing before and after bonding on both the top and bottom of the thin film material. Thus in the case of strain modulated epitaxy, the thin film substrate can be patterned and subsequently bonded with the pattern on the bottom, leaving an unpatterned epitaxial layer as the thin film compliant substrate growth surface. There have been numerous demonstrations of this type of materials processing for semiconductor

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devices, including those in the GaAs[14] and InP[15] material systems, bonded to a variety of substrates for multimaterial integration, and in many cases, device performance has been enhanced.[16]

We have shown that the dislocation defect density produced during the strain relaxation process is lower for the growth of thin (200–400 nm) $In_{0.1}Ga_{0.9}As$ films on GaAs thin compliant substrates 250–500 nm thick than for the growth on GaAs conventional substrates,[13] thus indicating that an effective means of producing compliant substrates. The GaAs compliant substrates were prepared using wet etching and were bonded to GaAs mechanical host substrates, which provides structural stability. In two consecutive experiments, 250 and 400 nm thick $In_{0.1}Ga_{0.9}As$ was grown simultaneously on both GaAs thin compliant substrates and conventional substrates. In both cases, fewer misfit dislocations were observed by Nomarski for the films on the compliant substrates. Double crystal x-ray diffraction measurements indicate that, for the 400 nm InGaAs layers, the degree of relaxation is greater for the epitaxial layer on the conventional substrates than on the thin film substrates.

The bonding between the thin substrate and the mechanical host substrate is extremely important. The bonding must be strong enough to hold the compliant substrate uniformly to the mechanical host during growth and potential subsequent processing, but the bonding must be weaker than the covalent bonding produced during growth, so that the deformation of the compliant substrate after the initiation of strained layer growth is enabled. The van der Waals bond, a room-temperature bond commonly used to bond thin films to mechanical host substrates, has been characterized to lie between rigid and weak. This bond becomes weak above room temperature, indicating that compliant substrates utilizing this bonding layer will be able to move freely at standard MBE growth temperatures.[17]

Since the strain in the epitaxial layer can be reduced using compliant substrates, patterned compliant substrates can be used, along with strain-dependent MBE growth kinetics, to achieve a lateral strain profile in the epitaxial film. This technique can be viewed as an inverted stressor approach, in which the three-dimensional geometry of a strained multilayer modifies the material deformation, plus the additional *and significant* effects realized by strain-induced modification of growth kinetics. The strain-dependent growth kinetics provide feedback to the inverted stressor structure by laterally modulating the composition and thickness of the growing epilayer. There are numerous strain-dependent growth kinetics which can be used to realize lateral variations in material properties including In desorption,[20–22] migration of adatoms,[18] two- to three-dimensional growth mode transition thickness[4] and movement and formation of As precipitates.[19] Figure 1 shows how this concept can be used, for example, to control the composition and thickness of a strained overlayer through the dependence of In desorption on strain during InGaAs growth. The pattern in the compliant substrate modulates the overlayer-to-substrate thickness ratio, and the strain at the surface of the epitaxial film is thus laterally controlled by this ratio. While the exact dependence of the activation energy for In desorption on strain for InGaAs growth on GaAs is not known, a number of studies indicate that this effect is significant.[20–22] Therefore, such a strain variation should lead to significant lateral changes in the In composition and thickness of the film *without any surface patterning or post-growth processing*. The geometry of the pattern and the growth kinetics will determine the magnitude of the lateral material variations. Stressor studies have shown that large stresses occur for many geometries at the pattern edge,[23] and therefore, it is possible that edge effects may dominate in the bottom-patterned substrates, creating large band gap modulations in quantum-sized regions. With larger pattern sizes, changes in band gap on the order of standard device geometries (tens to hundreds of μm) are anticipated, which is similar to the control of In desorption via temperature variations during MBE growth.[24]

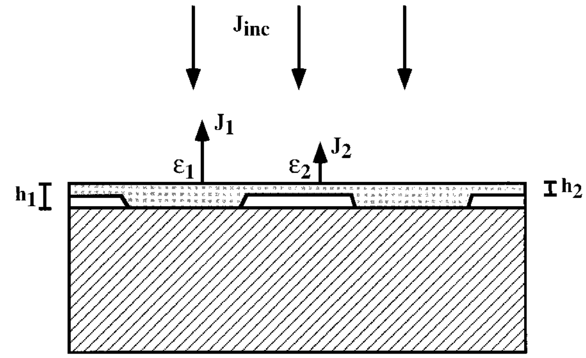

FIG. 1. Schematic indicating varying In desorption across the surface of a thin, bottom-patterned substrate. J_{inc} in the In flux incident on the sample. The In desorption fluxes from the two different regions of the pattern, J_1 and J_2, are dependent on the properties of the pattern, i.e., pattern thickness h_1 and h_2 and overlayer strain ϵ_1 and ϵ_2.

We have grown on bottom-patterned GaAs thin compliant substrates which are bonded to mechanical host substrates. The structure used to create the compliant substrates consisted of a 2 μm GaAs epitaxial layer on top of an AlAs sacrificial layer grown on a GaAs substrate by MBE. Standard photolithography was used to pattern 10 μm stripes separated by 10 μm and $H_2SO_4:H_2O_2:H_2O$ was used to etch the stripes 200 nm into the material. The structure was then bonded to a GaAs mechanical host substrate using a hybrid van der Waals/indium metal bond. The entire sample was immersed in an HF solution for several hours, during which time the AlAs layer was selectively etched, separating the 2 μm patterned GaAs layer from the GaAs growth substrate. The thicknesses of the thin GaAs compliant substrates bonded to the GaAs host substrates were 400 and 200 nm in the unetched and etched stripe areas, respectively. The final substrate design is shown in Fig. 1. Thin layers of $In_{0.1}Ga_{0.9}As$ films were grown on these thin patterned GaAs compliant substrates and on conventional GaAs substrates simultaneously by MBE to compare the morphology of the films under several growth conditions.

To assess the compliant substrates in a growth regime where growth kinetics should not significantly depend on strain, 250 nm thick $In_{0.1}Ga_{0.9}As$ was grown on bottom-patterned compliant substrates at 480 °C. The good surface morphology of the film indicates that no obvious extrinsic effects from the compliant substrate process degraded the material properties. Similar results were observed previously

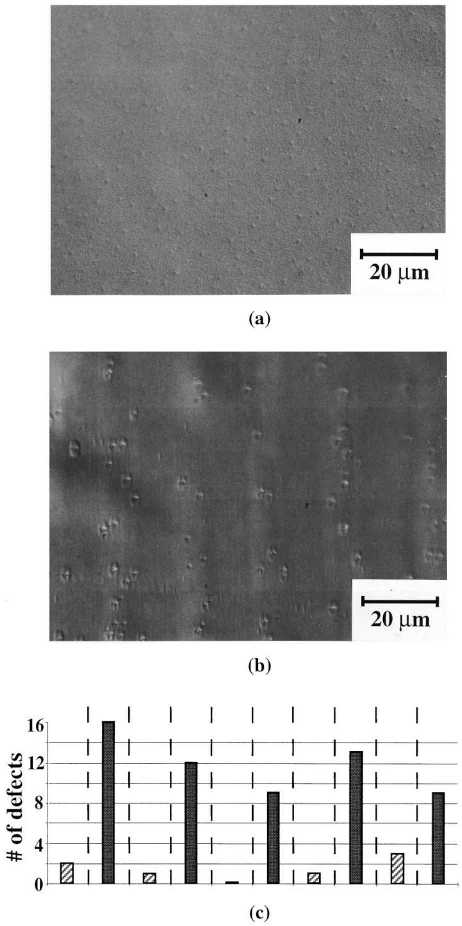

FIG. 2. Patterned GaAs substrates after the growth of 2500 Å $In_{0.1}Ga_{0.9}As$ at (a) 520 °C and (b) 580 °C. (c) Shows a bar graph of the number of defects corresponding spatially to the thin (solid) and thick (striped) regions of the pattern in (b).

on unpatterned compliant substrates.[13] Subsequently, two consecutive growth of $In_{0.1}Ga_{0.9}As$ were performed on bottom-patterned thin compliant substrates at 520 and 580 °C. Some In desorption from the surface was expected at 580 °C,[20] whereas it was not expected to occur at 520 °C. Figure 2 shows Nomarski photographs of samples grown at (a) 520 °C and (b) 580 °C. The patterned compliant substrate sample grown at 520 °C had good morphology and no growth- or pattern-dependent characteristics. In contrast, the sample grown at 580 °C exhibited a high density of oval defects, which are clearly aligned with the pattern on the bottom of the compliant substrate. The graph in Fig. 2(c) is the defect density corresponding spatially with Fig. 2(b), where the dark bars indicate the defect density in the thin stripe regions and the cross-hatched bars represent the thicker stripes. Further investigation is needed to determine the mechanism which caused the defects to form along the pattern template. It is possible that the oval defects spatially correspond to the transition between the thick and thin regions of the pattern where the stress is high. More sensitive measuring techniques are needed to confirm this theory. It is clear, however, that the pattern perturbed the growth of the strained material; this is the first observation of such an effect.

In conclusion, we have proposed the use of a new technique called strain modulated epitaxy to achieve lateral control of material properties during epitaxial growth. This concept utilizes bottom-patterned thin compliant substrates to achieve a lateral strain profile during growth, which in turn can be used to modify growth kinetics. We have demonstrated initial growths of InGaAs thin films on these GaAs thin compliant substrates. These experiments have shown that the bonding does not degrade the surface morphology during growth, and that the pattern on the bottom of the compliant substrates influences the growth of the strained layer on the surface at temperatures where growth kinetics depend on strain.

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